Nd-Fe-B TYPE ANISOTROPIC EXCHANGE SPRING MAGNET
AND METHOD OF PRODUCING THE SAME

BACKGROUND OF THE INVENTION

[0001]   The present invention relates to a rare earth
5   permanent magnet having anisotropy and a method of
producing the magnet.

[0002]   Nd-Fe-B type permanent magnets have been widely
used as a magnet for a motor. Such magnets have been
produced by means of a melting method disclosed in M.
10   Sagawa et al., Japanese Journal of Applied Physics 26
(1987) 785 or a quenching method disclosed in R. W. Lee,
Applied Physics Letter 46 (1985) 790. Further, it is
possible to produce magnet powder having anisotropy by
means of a HDDR treatment disclosed in T. Takeshita et
15   al., Proc. 10th Int. Workshop on Rare Earth Magnets and
Their Applications, Kyoto, (1989) 511.

[0003]   The magnetic properties of Nb-Fe-B type
permanent magnets have approached a theoretical limit,
and therefore it is desired to develop next-generation
20   high-performance magnets. One of the next-generation
magnets is an exchange spring magnet, which is also
called nano-composite magnet, as disclosed in E. F.
Kneller and R. Hawig, IEEE Transaction Magnetics 27
(1991) 3588. Such an exchange spring magnet has a
25   structure where hard magnetic phases and soft magnetic
phases are finely dispersed at intervals of several tens
nm. The exchange spring magnet performs like as a unit
hard magnetic phase as a whole since the magnetization of
the soft magnetic phases is not easily reversed for the
30   reason that the magnetizations of the hard and soft
magnetic phases are coupled by the exchange interaction

therebetween. Accordingly, it has been evaluated that the nano-composite magnet has a possibility for functioning as a very high-performance magnet. For example, it has been reported in R. Skomski and J. M. D.

5   Coey, Physical Review B48 (1993) 15812 such that if $Sm_2Fe_{17}N_3/Fe$ type alloy can have a property of anisotropy, (BH)max=137MGOe will be theoretically obtained.   A producing method of $Nd_2Fe_{14}B/Fe_3B$ type exchange spring magnet has been proposed in R. Coehoorn et al., Journal

10 de Physique 49 (1988) C8-669. Further, a producing method of $Nd_2Fe_{14}B/Fe$ type exchange spring magnet has been proposed in Japanese Patent Provisional Publication Nos. 7-173501 and 7-176417 and in L. Withanawasam et al., Journal of Applied Physics 76 (1994) 7065.

15 [0004]   However, a melt spun method or mechanical alloying (MA) method employed in the above magnet producing methods cannot produce the magnet having the magnetic anisotropy, and therefore the property of the obtained exchange spring magnet is not sufficient as

20 compared to the theoretical property.

[0005]   Furthermore, various producing methods of an anisotropic exchange spring magnet have been proposed. For example, Japanese Patent Provisional Publication No. 11-8109 has disclosed a producing method of crystallizing

25 Nd-Fe-B amorphous alloy by heating in a high magnetic field. Japanese Patent Provisional Publication No. 11-97222 has disclosed a producing method of hot working a quenched thin strip alloy so that hard and soft magnetic phases are finely and dispersedly precipitated.

30 Japanese Patent Provisional Publication No. 2000-235909 has disclosed a method of directly producing a magnet having the anisotropy by executing a warm-working

uniaxial-deformation under a liquid phase existing condition of the raw material.

SUMMARY OF THE INVENTION

[0006]   However, it is further required to improve the magnetic property of an anisotropic exchange spring magnet and to develop a method of easily producing such an improved anisotropic exchange spring magnet.

[0007]   It is therefore an object of the present invention to provide a Nd-Fe-B type anisotropic exchange spring magnet having a superior magnetic property and to provide a method of producing the Nd-Fe-B type anisotropic exchange spring magnet.

[0008]   It is another object of the present invention to provide a magnet alloy and powder thereof which are used in producing the exchange spring magnet.

[0009]   It is a further object of the present invention to provide a motor which comprises the Nd-Fe-B type anisotropic exchange spring magnet.

[0010]   An aspect of the present invention resides in a Nd-Fe-B type rare earth magnet alloy which comprises hard magnetic phases and soft magnetic phases, wherein a minimum width of the soft magnetic phases is smaller than or equal to 1 μm and a minimum distance between the soft magnetic phases is greater than or equal to 0.1 μm.

[0011]   Another aspect of the present invention resides in powder of a Nd-Fe-B type rare earth magnet alloy which comprises hard magnetic phases and soft magnetic phases, wherein a minimum width of the soft magnetic phases is smaller than or equal to 1 μm and a minimum distance between the soft magnetic phases is greater than or equal to 0.1 μm.

[0012]   A further aspect of the present invention
resides in a method of producing powder of a Nd-Fe-B type
rare earth magnet alloy which comprises hard magnetic
phases and soft magnetic phases wherein a minimum width

5   of the soft magnetic phases is smaller than or equal to 1
μm and a minimum distance between the soft magnetic
phases is greater than or equal to 0.1 μm. The method
comprises pulverizing the Nd-Fe-B type rare earth magnet
alloy by means of a ball mill using a dispersant under a

10   non-oxidation atmosphere.

[0013]   A further aspect of the present invention
resides in a method of producing a Nd-Fe-B type
anisotropic exchange spring magnet, which method
comprises obtaining powder of a Nd-Fe-B type rare earth

15   magnet alloy which comprises hard magnetic phases and
soft magnetic phases wherein a minimum width of the soft
magnetic phases is smaller than or equal to 1 μm and a
minimum distance between the soft magnetic phases is
greater than or equal to 0.1 μm, obtaining a compressed

20   powder body by compressing the powder at a compressing
pressure ranging from 1 to 5 ton/cm^2 in a magnetic field
ranging from 15 to 25 kOe, and obtaining a bulk magnet by
sintering the compressed powder body at a temperature
ranging from 600 to 800 °C and at a compressing pressure

25   ranging from 1 to 10 ton/cm^2 in a discharge plasma
sintering unit.

[0014]   A further aspect of the present invention
resides in a Nd-Fe-B type anisotropy exchange spring
magnet produced by a method of obtaining powder of a

30   Nd-Fe-B type rare earth magnet alloy which comprises hard
magnetic phases and soft magnetic phases wherein a

minimum width of the soft magnetic phases is smaller than or equal to 1 μm and a minimum distance between the soft magnetic phases is greater than or equal to 0.1 μm; obtaining a compressed powder body by compressing the

5   powder at a compressing pressure of 1 through 5 ton/cm^2 in a magnetic field ranging from 15 to 25 kOe; and obtaining a bulk magnet by sintering the compressed powder body at a temperature ranging from 600 to 800 °C and at a compressing pressure ranging from 1 to 10 ton/cm^2 in a

10   discharge plasma sintering unit.

[0015]   A further aspect of the present invention resides in a motor which comprises a magnet produced by a method of obtaining powder of a Nd-Fe-B type rare earth magnet alloy which comprises hard magnetic phases and

15   soft magnetic phases wherein a minimum width of the soft magnetic phases is smaller than or equal to 1 μm and a minimum distance between the soft magnetic phases is greater than or equal to 0.1 μm, obtaining a compressed powder body by compressing the powder at a compressing

20   pressure of 1 to 5 ton/cm^2 in a magnetic field ranging from 15 to 25 kOe, and obtaining a bulk magnet by sintering the compressed powder body at a temperature ranging from 600 to 800 °C and at a pressure ranging from 1 to 10 ton/cm^2 in a discharge plasma sintering unit.

25   [0016]   The other objects and features of this invention will become understood from the following description with reference to the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0017]   Fig. 1 is a scanning electron microscope (SEM)

30   photograph showing a cross section of a rare earth magnet

alloy (having a composition of $Nd_{9.1}Fe_{75.8}Co_8B_{6.1}V_1$) of EXAMPLE I according to the present invention.

[0018]   Fig. 2 is a graph showing magnetization curves of a VSM sample produced from a thin strip alloy of EXAMPLE 1.

[0019]   Fig. 3 is a graph showing magnetization curves measured for checking a spring back phenomenon of the thin strip alloy of EXAMPLE 1.

[0020]   Fig. 4 is an enlarged view of the graph of Fig. 3 amplified in the horizontal axis ten times.

[0021]   Fig. 5 is a scanning electron microscope (SEM) photograph showing powder of the rare earth magnet alloy (having a composition of $Nd_{9.1}Fe_{75.8}Co_8B_{6.1}V_1$) of EXAMPLE 1.

[0022]   Fig. 6 is a graph showing magnetization curves of a VSM sample produced from the as-milled magnet powder of EXAMPLE 1.

[0023]   Fig. 7 is a graph showing magnetization curves for checking the spring back phenomenon of Fig. 6 in the parallel direction.

[0024]   Fig. 8 is a graph showing magnetization curves of a VSM sample produced from heat-treated magnet powder of EXAMPLE 1.

[0025]   Figs. 9A and 9B are charts showing X-ray diffraction analysis results of the as-milled powder (A) of EXAMPLE 1 and the powder (B) which was obtained by heat treating the powder (A) at 612°C.

[0026]   Fig. 10 is a SEM photograph showing a cross section of the rare earth magnet alloy (having a composition of $Nd_{11}Fe_{72}Co_8B_{7.5}V_{1.5}$) of EXAMPLE 4.

[0027]   Fig. 11 is a graph showing magnetization curves of a VSM sample produced from the as-milled magnet powder of EXAMPLE 4.

[0028]   Fig. 12 is a graph showing magnetization curves of a VSM sample produced from the heat-treated magnet powder of EXAMPLE 4.

[0029]   Fig. 13 is a graph showing magnetization curves for checking the spring back phenomenon of the heat-treated magnet powder of EXAMPLE 4.

[0030]   Fig. 14 is a cross sectional view showing a 1/4 part of a concentrated winding and surface permanent magnet type motor employing the exchange spring magnet.

DETAILED DESCRIPTION OF THE INVENTION

[0031]   Inventors of the present invention found that it was possible to obtain a Nd-Fe-B type anisotropic exchange spring magnet having a superior magnetic property by using a rare earth magnet alloy containing soft magnetic phases and hard magnetic phases in a predetermined condition, as starting material. Further, the inventors found that it was preferable to employ a ball-mill to pulverize the starting material in producing the Nd-Fe-B type anisotropic exchange spring magnet and further found a preferable production condition for producing the Nd-Fe-B type anisotropic exchange spring magnet.

[0032]   First, a producing method of the anisotropic exchange spring magnet is briefly discussed. By means of a strip casting method, the rare earth magnet alloy according to the present invention is obtained. Fig. 1 is a SEM photograph showing a cross-section of the rare earth magnet alloy, whose composition is $Ni_{9.1}Fe_{75.8}Co_8B_{6.1}V_1$, according to the present invention. In Fig. 1, whitish bubble-shaped parts and whitish needle-shaped parts are soft magnetic phases. Throughout the description of the present invention, "soft magnetic phase" is a part

recognized in the photograph having the scale factor as same as that in Fig. 1. More specifically, the soft magnetic phase having a size smaller than 0.1μm in Fig. 1 is excluded from "soft magnetic phase" defined in the

5 present invention. Further, other darkish part except for "soft magnetic phase" is "hard magnetic phase". The "hard magnetic phase" is a hard magnetic phase region like as a mono-crystal. In pulverizing process of the magnet alloy, a size of power becomes smaller than a size

10 of the hard magnetic phase region of the magnet alloy. · More specifically, in the pulverizing process, a crystalline grain size of the hard magnetic phases becomes fine by the repetition of cross-slip of crystals. Further, cross-slip of the crystals including the soft

15 magnetic phases is also repeated in the pulverizing process. Therefore, the powder obtained by the pulverizing process includes the soft magnetic phases of fine size in addition to the hard magnetic phases of fine size.

20 [0033]   Even after the magnet alloy is pulverized into a size smaller than a size of the hard magnetic phase region, each fine-size hard magnetic phase in the obtained power maintains the crystal orientation as same as that of the original hard magnetic phase. The hard

25 magnetic phases of the obtained powder contain strains generated during pulverizing process using a ball mill. By executing the heat treatment subsequently to the pulverizing process, the hard magnetic phases of the obtained powder change into the fine hard magnetic phases

30 which have recovered the magnetic property and in which the axes of the easy magnetization are aligned. As discussed above, the powder obtained by pulverizing the

alloy using a ball mill also includes fine soft magnetic phases in addition to the hard magnetic phases. Accordingly, the heat treatment of the power provides a further superior anisotropic rare earth magnet powder

5   (anisotropic exchange spring magnet powder) in which the soft magnetic phases and the hard magnetic phases whose axes of easy magnetization are aligned are mixed.

[0034]   Subsequently, there will be discussed methods of conveniently checking that the rare earth magnet alloy

10 comprises the soft magnetic phases in addition to hard magnetic phases and that the hard magnetic phase region is formed into like a mono-crystal, that is, methods of conveniently checking the alignment of the crystal orientation.   One of the methods is a method of checking

15 the magnetic property of the exchange spring magnet which was practically produced.   First, a magnet to be checked is obtained by pulverizing the magnet alloy using a ball mill, by producing a compressed powder body by means of a compressing process in a magnetic field, and by sintering

20 the compressed powder body under the temperature lower than 800°C using an electro-discharge plasma apparatus so as to produce a bulk magnet.   Subsequently, the degree of the anisotropy of the bulk magnet is checked by comparing a magnetization curve along the direction parallel to the

25 magnetic field direction applied during the compressing process and a magnetization curve along the direction perpendicular to the magnetic field direction during the compressing process.   When the anisotropy of the bulk magnet is confirmed, it is determined that the hard

30 magnetic phase regions are put in an estimated condition.

[0035]   Another method is a simple method.   First, a sample for a vibrating sample magnetometer (VSM) is

produced by pulverizing thin strips of a rare earth
magnet alloy, by mixing the obtained powder with epoxy
resin functioning as adhesive and by hardening the
mixture poured in a VSM sample container while being put
5   in a magnetic field. Subsequently, there are measured a
magnetization curve of a parallel-set sample which is set
in the VSM so that the magnetic field applied to the
sample by the VSM is parallel to the direction of the
magnetic field applied during the sample producing
10   process and the magnetization curve of the
perpendicular-set sample which is set in the VSM so that
the magnetic field applied to the sample by the VSM is
perpendicular to the direction of the magnetic field
applied during the sample producing process. Finally,
15   the degree of mono-crystal like of the hard magnetic
phase region, which degree is indicative of the
anisotropy of the produced sample, is estimated from the
ratio (Js ratio) between the magnetizations (Js) of the
parallel-set sample and the perpendicular-set sample at
20   the measured maximum magnetic field of 16kOe. It is
preferable that the thin strip of the rare earth magnet
alloy is further finely pulverized. However, in this
embodiment, the size of the obtained powder has been
determined to be smaller than or equal to 25μm for the
25   reasons that this size of 25μm is a limit which is
capable of being manually produced by pulverizing the
material using a mortar and pestle and classifying the
obtained powder using sieves. It is assumed that the
crystal orientations of adjacent hard magnetic phase
30   regions are almost aligned, that is, they are textured.
     [0036]   The latter method is an effective means for the
development of the rare earth magnet alloys. As a result

of actually producing exchange spring magnets, when a
rare earth magnet alloy having a Js ratio greater than
1.3 was employed as starting material, it became possible
to produce an anisotropic exchange spring magnet

5   therefrom. As discussed above, the Js ratio is a ratio
between the magnetizations (Js) of the parallel-set
sample and the perpendicular-set sample at the measured
maximum magnetic field. Further, the Js ratio of a bulk
magnet produced from the same alloy was greater than the

10   Js ratio of the VSM sample produced by this method.

[0037]   By compressing the rare earth magnet powder in
a condition of a predetermined magnetic field and a
predetermined pressure, a compressed powder body (green
compact) having the anisotropic property is obtained.

15   Further, by sintering the green compact under a relative
low temperature so as not to grow crystals thereof, a
Nd-Fe-B type anisotropic exchange spring magnet having a
superior magnetic property is obtained. With the thus
method, the aimed magnet is easily obtained.

20   [0038]   The inventors of the present invention found
that a superior anisotropic exchange spring magnet was
obtained when Nd-Fe-B type rare earth magnet alloy
employed as starting material has a structure wherein
hard magnetic phases and soft magnetic phases are mixed

25   so as to satisfy a predetermined condition, as a result
of due consideration taking account of the properties and
the productivity of various anisotropic exchange spring
magnets. That is, the inventors reached a first aspect
of the present invention that a Nd-Fe-B type rare earth

30   magnet alloy having a mixed structure of the hard
magnetic phases and soft magnetic phases is characterized
such that the minimum width of the soft magnetic phase is

substantially smaller than or equal to 1 μm and the
minimum distance between the soft magnetic phases is
substantially greater than or equal to 0.1 μm.

[0039]   Herein, there are explained the minimum width

5   of soft magnetic phase and the minimum distance between
soft magnetic phases, with reference to Fig. 1. As
already defined, "soft magnetic phase" is a soft magnetic
phase which is recognized in the photograph having the
scale factor in Fig. 1, and particularly has a size

10   greater than or equal to 0.1 μm. "Minimum width of soft
magnetic phase" in the present invention is a minimum
value of a width of a soft magnetic phase detected when
the rare earth magnet alloy is observed. As to a
bubble-shaped soft magnetic phase, a length denoted by D1

15   in Fig. 1 corresponds to the minimum width in this soft
magnetic phase. As to a needle-shaped soft magnetic
phase, a width D2 at a portion except for end portions
corresponds to the minimum width in this soft magnetic
phase. On the other hand, "minimum distance between soft

20   magnetic phases" is a distance between the bubble-shaped
soft magnetic phase and the soft magnetic phase which is
most adjacent to this bubble-shaped soft magnetic phase.
The distances denoted by D3 and D4 in Fig. 1 correspond
to the minimum distance between soft magnetic phases. As

25   to the needle-shaped soft magnetic phase, the minimum
distance is also a distance between the needle-shaped
soft magnetic phase and the soft magnetic phase which is
most adjacent to this needle-shaped soft magnetic phase.

[0040]   Throughout the explanation of the present

30   invention, a sentence "the minimum width is substantially
smaller than or equal to 1 μm" means that more than 90%
of the minimum widths of the respective soft magnetic

phases are smaller than or equal to 1 μm when the soft
magnetic phases are selected at random in a SEM
photograph. For example, when 10 soft magnetic phases
are selected at random, the number of the soft magnetic
5   phases having the minimum width smaller than 1 μm may be
9 or 10. It is preferable that all of the soft magnetic
phases have the minimum width smaller than 1 μm.
Similarly, a sentence "minimum distance is substantially
greater than or equal to 0.1 μm" means that more than 90%
10   of the minimum distances of the respective soft magnetic
phases are greater than or equal to 0.1 μm when the soft
magnetic phases are selected at random in a SEM
photograph. For example, when 10 soft magnetic phases
are selected at random, the number of the soft magnetic
15   phases having the minimum distance greater than or equal
to 0.1 μm may be 9 or 10. It is preferable that all of
the soft magnetic phases have the minimum distance
greater than or equal to 0.1 μm. The minimum width and
the minimum distance of the soft magnetic phases may be
20   calculated by a method of observing a cross section of
the magnet alloy by means of SEM (scanning electron
microscope). The calculation procedure is not limited to
this method and may be executed by other method.
Although the recognition of the hard magnetic phases can
25   be executed using TEM (transmission electron microscopy),
it may be executed by means of a deductive reasoning as
discussed above, as far as no problem occurs.
[0041]   When the minimum width of the soft magnetic
phase and the minimum distance between the soft magnetic
30   phases satisfy the above-discussed values, the
anisotropic exchange spring magnet has the superior

properties. The reason thereof is that if the minimum distance between the soft magnetic phases is too small, that is, if the distance between the soft magnetic phases is too short, the hard magnetic phase region becomes too

5   small. Therefore, it will become difficult to obtain the magnet powder wherein the hard magnetic phases are fine, the axes of easy magnetization of the hard magnetic phases are aligned, and the size of the magnet powder is greater than 0.1 μm. Further, if the minimum width of

10   the soft magnetic phase is too large, that is, if the soft magnetic phase is too large, it will cause the problem that the pulverizing of the starting material would increase a difficulty.

[0042]   The preferable compositions of the magnet

15   material for obtaining the exchange spring magnet can be represented by the following chemical formula (1).

$$Nd_xFe_{100-x-y-z}B_yV_z \qquad \text{---(1)}$$

[0043]   It was estimated from X-ray diffraction analysis and measurement of the temperature dependency as

20   to the magnetization such that in these compositions the hard magnetic phase was $Nd_2Fe_{14}B$, and the soft magnetic phase was α-Fe.

[0044]   The compositions of Nd-Fe-Co-B type rare-earth magnet alloy are, for example, $Nd_xFe_{85-x}Co_8B_6V_1$ wherein x is

25   within a range from 9 to 11. That is, by using the rare-earth magnet ally having these compositions, an anisotropic exchange spring magnet having a superior magnetic property is obtained. It was estimated that the hard magnetic phase of the magnet having these

30   compositions was $Nd_2(Fe-Co)_{14}B$, and the soft magnetic phase was α-(Fe-Co), from the X-ray diffraction analysis

and the measurement of the temperature dependency as to the magnetization of the produced magnet. However, the composition is not limited to these compositions, and it is preferable that x, y and z in the chemical formula (1) are respectively within the ranges discussed hereinafter. Further, the elements of the composition of Nd-Fe-Co-B rare-earth magnet alloy may be replaced with the elements discussed later by a predetermined quantity.

[0045]   It is preferable that x in the chemical formula (1) ranges from 9 to 11. If the quantity of Nd becomes greater than 11 atom%, the ratio of the soft magnetic phase becomes smaller than 5%. This lowers the properties of the exchange spring magnet. On the other hand, if the quantity of Nd becomes smaller than 9 atom%, the difficulty of producing the rare-earth magnet alloy increases.

[0046]   It is preferable that y in the chemical formula (1) ranges from 5 to 8. If the quantity of B becomes greater than 8 atom%, there is a possibility that other phase except for the phase of $Nd_2Fe_{14}B$ and the phase of α-Fe is produced. On the other hand, if the quantity of B becomes smaller than 5 atom%, the difficulty of producing the rare-earth magnet alloy increases.

[0047]   It is preferable that z in the chemical formula (1) ranges from 0 to 2. V is added in the rare-earth magnet to improve the fineness of crystals and the increase of coercivity. This addition is not essential and may be cancelled. However, if this addition is excessive, there is increased a possibility of lowering the magnetic property.

[0048]   Nd may be replaced with Pr within a range from 0.01 to 80 atom%. It is preferable that Nd is replaced

with Pr within a range from 20 to 60 atom%. When the
quantity of the replacement with Pr is within a range
from 20 to 60 atom%, the residual flux density is almost
maintained, and the coercive force and the rectangular
5   characteristic in the magnetization curve are improved.
[0049]   Nd may be replaced with Dy or Tb within a range
from 0.01 to 10 atom%. When the quantity of this
replacement with Dy or Tb is within a range from 0.01 to
10 atom%, it is possible to improve the coercive force
10   and the thermal property without largely lowering the
residual flux density.
[0050]   A part of Fe may be replaced with Co. When the
part of Fe is replaced with Co, it is preferable that the
replacement percentage is within a range from 0.01 to 30
15   atom%. This replacement within this range improves the
thermal properties without degrading the coercive force
and the residual flux density. In particular, when the
quantity of the replacement with Co is within 5 to 20
atom%, it is possible to improve the residual flux
20   density in addition to the thermal properties. It was
estimated that when Fe was replaced with Co, the hard
magnetic phase was $Nd_2(Fe-Co)_{14}B$, and the soft magnetic
phase was α-(Fe-Co), from a result of the X-ray
diffraction analysis and the measurement of the
25   temperature dependency of the magnetization.
[0051]   Fe or Co in Fe-Co may be replaced with a small
quantity of at least one of Al, Mo, Zr, Ti, Sn, Cu, Ga
and Nb. This replacement promotes a microstructure of
the magnet alloy and increases the coercive force.
30   However, when the quantity of this replacement becomes
excessive, the magnetic property may be rather degraded.
From this viewpoint, it is preferable that the quantity

of element to be replaced is within a range from 0.1 to 3 atom% with respect to the all composition.

[0052]   It is impossible to completely eliminate a minute quantity of impurities since the magnet according to the present invention is alloy material. However, it is preferable that the quantity of the impurities is as small as possible, and preferable that the amount of the impurities is smaller than or equal to 1 weight%.

[0053]   The magnet alloy according to the present invention is produced by the following procedures. First, metal elements for the magnet alloy is mixed to achieve a desired composition. The properly mixed metal elements are melted by a commonly known melting method such as a high-frequency induction melting method under a vacuum or argon atmosphere, and an ingot of the desired-composition magnet alloy is obtained by solidifying the melted alloy. Thereafter, the rare earth magnet alloy such as a crystalline thin strip alloy according to the present invention is obtained by a quenching method such as a strip casting method wherein the melted magnet alloy is quenched and changes into crystalline thin strip alloy. Such a strip casting method is executed using a commonly known apparatus without specially improving this apparatus. It is of course that the improvement of the apparatus is preferable to further preferably obtain the desired magnet alloy.

[0054]   Generally, it is difficult to uniquely determine a producing condition into one condition and it is necessary to properly set each condition according to the employed apparatus and the kind of alloys. In particular, it is important to finely control a cooling speed in producing the magnet alloy according to the

present invention. If the cooling speed is out of the
aimed cooling speed range, there will degrade the
properties of the magnet alloy such that the size of
crystals increases or the thin strip alloy degrades in
5   homogeneity. For example, if the cooling speed is too
high, the thickness of the thin strip alloy is decreased,
and if too slow, the thickness of the thin strip alloy is
increased. Thus, the cooling speed is closely related
with the thickness of the thin strip alloy produced by
10   the strip casting method. In producing the thin strip
magnet alloy according to the present invention, it is
preferable that the cooling speed is controlled such that
the thickness of the thin strip alloy ranges from 30 to
300 μm. For example, it is preferable that the cooling
15   speed is set at 1000°C/sec or more.

[0055]   Powder of the rare earth magnet alloy is
obtained by pulverizing the rare earth magnet alloy
according to the present invention into powder. It is
preferable that the pulverizing of the rare earth magnet
20   alloy is executed using a ball mill. Another aspect of
the present invention, therefore, resides in the powder
of the rare earth magnet alloy which powder is obtained
by pulverizing the rare earth magnet alloy according to
the first aspect of the present invention using a ball
25   mill. A further aspect of the present invention resides
in a producing method of the rare earth magnet powder
which is produced by pulverizing the rare earth magnet
alloy of the first aspect of the present invention using
a ball mill under a non-oxidizing atmosphere while adding
30   dispersing agent.

[0056]   It is preferable that the rare earth magnet
alloy is pulverized into a size smaller than or equal to

a size of the hard magnetic phase region using a ball

mill. For example, when the size of the hard magnetic

phase region is 0.5 μm, it is preferable that the rare

earth magnet alloy is pulverized into a size smaller or

5   equal to 0.5 μm. Usually, the magnet alloy is pulverized

into powder having a size of sub-micron size ranging from

0.1 to 1.0 μm. In view of preferably realizing the

magnetic field orientation of the magnet powder, it is

preferable that the magnet alloy is pulverized into this

10   sub-micron size. Although a lower limit of the size of

the magnet powder is not determined, if the size of the

magnet powder is too small, it becomes hard for the

magnet powder to exhibit the magnetic field orientation.

Further, the oxidation durability of the magnet powder

15   degrades as the size of the magnet powder becomes smaller.

Consequently, it is preferable that the size of the

magnet powder is greater than or equal to 0.1 μm.

[0057] A type of the ball mill is not limited to a wet

type or dry type. It is preferable that the magnet alloy

20   is pulverized under a non-oxidizing atmosphere such as

argon atmosphere or nitrogen atmosphere, in order to

prevent the magnetic property of the magnet powder from

being degraded by the oxidation of the magnet powder.

When a wet type ball mill is employed in pulverizing the

25   material, cyclohexane or the like is used. Further, in

order to suppress the aggregation of the obtained powder,

dispersion agent is employed. This also effectively

functions in applying the magnetic field orientation to

the produced magnet powder. A typical dispersion agent

30   employed in a wet type ball mill is succinic acid, and a

typical dispersion agent employed in a dry type ball mill

is stearic acid. It was estimated on the basis of the

magnetic measurement and the X-ray diffraction analysis
that the as-milled powder was partially changed from
crystalline to amorphous.

[0058]   Further, by heat treating the powder obtained

5   by pulverizing the magnet ally, the power changes into
further improved powder of an anisotropic rare earth
magnet alloy (exchange spring magnet) where there are
mixed the soft magnetic phases and the hard magnetic
phases whose axes of the easy magnetization are aligned.

10   For example, it is preferable that the temperature of the
heat treatment for the obtained powder is controlled
within a range from 500 to 800°C.

[0059]   The heat-treated magnet powder is therefore put
in a condition that the hard magnetic phases and the soft

15   magnetic phases are finely mixed. Further, the easy
magnetization axes of the hard magnetic phases are
aligned. As already explained, the mono-crystal-like
hard magnetic phases function to pulverize the alloy into
fine crystalline size hard magnetic phases during the

20   ball mill process and to disperse fine soft magnetic
phases in the hard magnetic phases.

[0060]   Subsequently, the compressed powder body (green
compact) is obtained by compressing the obtained power in
a die while applying the magnetic field. The purpose of

25   the magnetic field application is the magnetic field
orientation of the powder to be compressed. The magnetic
field orientation of the powder is basically completed by
the application of the magnetic field before starting an
actual compression of the powder. The device employed in

30   the treatment for the magnetic field orientation and in
the compressing process is not limited to a special
device and may employ various commonly-known treatment

means. For example, this means may include a means for compressing the magnet powder under a condition where the axes of easy magnetization of the magnet powder are aligned in the same direction by the application of the

5   magnetic field. (Here, the axis of easy magnetization of the magnet powder is parallel to the axes of easy magnetization of the fine hard magnetic phases.) When this means is employed, it is appropriate that the compressing pressure is set within a range between from 1

10   to 5 tons/cm^2 and the magnetic field is set within a range between from 15 to 25 kOe. Also, it is preferable that the compressed powder body is produced using a die assembly for a discharge plasma sintering unit. That is, after compressing the powder in the die assembly and

15   transferring to the discharge plasma sintering unit, the compressed powder body in the assembly die is sintered by the discharge plasma sintering unit while the compressing pressure is applied to the compressed power body via the assembly die. This sintering process is preferable in

20   view of facilitating the workability of producing the magnet.

[0061]   A bulk of the anisotropic exchange spring magnet is obtained by executing a sintering process of the obtained compressed powder body under a compressed

25   state in a discharge plasma sintering unit. The use of the compressing and sintering technique in the discharge plasma enables the compressed powder body to be sintered at a relatively low temperature and thereby suppressing the formation of the coarse crystals and ensuring a

30   magnet having the superior properties. Also, the discharge plasma compressing and sintering technique may be executed using a general device, such as a device

"Model SPS-2040" made and sold by Izumitec Co. Ltd. and may be executed with a suitably improved device depending on a produced magnet to be obtained or a desired production line.

5   [0062]   Accordingly, if the temperature of the discharge plasma compressing and sintering process is too high, there may cause forming the coarse crystals, degrading coercive force, and weakening the exchange coupling.   In order to prevent these problems, it is

10   preferable that the solidifying process is executed at a temperature equal to or less than 800°C, more preferably equal to or less than 700°C.   In contrast, if the temperature of the discharge plasma compressing and sintering process is too low, the compressed powder body

15   is insufficiently densified, and therefore it is preferable that the temperature during such process is maintained at a temperature equal to or higher than 600°C.

[0063]   Further, it is preferable that such a compressing and sintering technique is executed under a

20   reduced pressure using a rotary pump, and it is appropriate that the temperature is raised at a temperature raising rate of approximately 15 to 25 K/min. It is difficult to uniquely define a retaining time period of the compressing and sintering technique since

25   there is a need for suitably changing the retaining time period according to various factors such as the device, the operating temperature, and the size of the compressed powder body.   Generally, the retaining time period is set at a value within approximately 0 to 10 min.   After the

30   temperature is maintained for a predetermined time period, the compressed powder body is cooled in the sintering apparatus at a temperature lowering rate between

approximately 10 to 30 K/min. In this instance, the
compressing pressure for the compressing and sintering
technique is appropriately selected from a range
approximately from 1 to 10 tons/cm^2. The discharge plasma

5   compressing and sintering process may be executed in a
condition out of the above-discussed condition as far as
the produced magnet has a crystalline size within an
allowable range and maintains the desired magnetic
property of the anisotropic rare earth magnet. The use

10   of such discharge plasma compressing and sintering
technique enables the bulk magnet with a low oxygen
concentration to be produced and thereby improving the
magnetic property of the produced magnet.

[0064] The magnitude of exchange-coupling is recognized

15   from the magnitude of the spring back behavior. The
heat-treated magnet powder exhibited the spring back
phenomenon, although it is of course possible to check
the spring back phenomenon from the finally obtained
anisotropic exchange spring magnet. Further, as it will

20   be predicted from the above discussion, the powder
obtained by pulverizing the base material using a ball
mill also exhibited the spring back phenomenon in the
second and third quadrants of the magnetization curve.

[0065] The present invention provides a method of

25   producing the Nd-Fe-B anisotropic exchange spring magnet
in such a manner as described above. That is, a further
aspect of the present invention resides in a producing
method of the Nd-Fe-B anisotropic exchange spring magnet
which method comprises a step of obtaining a compressed

30   powder body by compressing the rare earth magnet powder
according to the present invention at a compressing
pressure ranging from 1 to 5 ton/cm^2 in a magnetic field

ranging from 15 to 25 kOe, and a step of obtaining a bulk
magnet by sintering the compressed powder body in a
discharge plasma apparatus under a condition that a
temperature is maintained within a range from 600 to 800°C

5   and a compressing pressure is maintained within a range
from 1 to 10 ton/cm^2.

[0066]   It is preferable that the Nd-Fe-B anisotropic
exchange spring magnet according to this aspect of the
present invention is a rare earth magnet having a bulk

10   density greater than 95% of the true density of the rare
earth magnet alloy. If the density of the exchange
spring magnet is greater than 95% of the true density,
the produced exchange spring magnet has a large energy
product (BHmax).

15   [0067]   The anisotropic exchange spring magnet
according to the present invention is very variable as a
use for various devices requiring high magnetic
properties. For example, the anisotropic exchange spring
magnet according to the present invention is applicable

20   to a motor. If the magnet is employed as a part of a
motor, it becomes possible to produce the motor into a
further compacted size since the magnet according to the
present invention has a magnetic flux larger than that of
a conventional magnet. Further, the magnet according to

25   the present invention has a superior thermal property.
The magnet according to the present invention is
advantageously applicable to a drive motor for an
electric vehicle, a hybrid electric vehicle (HEV) and a
fuel cell vehicle (FCV), due to the superior properties

30   of the magnet. The reason that the magnetic flux of the
magnet according to the present invention is greater than
that of a sintered magnet depends on a fact that the

exchange spring magnet according to the present invention contains soft magnetic phases. Further, it is deemed that the reason for performing the superior thermal property depends on the coercive force mechanism. That

5   is, it is estimated that the coercive force mechanism of the magnet according to the present invention is similar to a pinning type although that of a common sintering magnet is a nucleation type. Due to this difference, it is seemed that the temperature stability of the magnet

10 according to the present invention is improved.

[0068]   Subsequently, there is discussed the present invention on the basis of EXAMPLES although the invention is not limited to these EXAMPLES.

[0069]   EXAMPLE 1

15   A thin strip of the rare earth magnet alloy was produced from an alloy ingot having a composition of $Nd_{9.1}Fe_{75.8}Co_8B_{6.1}V_1$ by means of the strip casting method. A condition of the strip casting method was that a cooling speed for cooling the melted alloy to a solidification

20 temperature of around 900°C was set at 2300°C/sec. By observing a cross-section of the thin strip alloy by means of a SEM (scanning electron microscope), it was confirmed that the thin strip alloy had a mixed structure of the hard magnetic phases and the soft magnetic phases.

25 Substantially the minimum width of the soft magnetic phase was smaller than or equal to 1 μm, and the minimum distance between the soft magnetic phases was greater than or equal to 0.1 μm. The thin strip alloy had a structure such that a surface of the thin strip facing a

30 roller of the strip casting method was more micro-structured than that of the other surface. Fig. 1 is a SEM photograph showing a center area of a cross

section of the obtained thin strip alloy. As discussed above, the whitish particles and the whitish needle like portions were precipitates of α-Fe, more restrictedly α-(Fe-Co). The other portion shown as a darkish region was

5 the hard magnetic phase region.

[0070]   Powder of a sample for VSM (vibrating sample magnetometer) was produced by pulverizing the thin strip alloy into a size smaller than 25 μm using a set of mortar and pestle. The VSM sample was produced by mixing

10 the obtained powder with epoxy adhesive and by solidifying the mixture poured in a VSM sample container in the magnetic field of 10kOe. Magnetization curves of the obtained VSM sample were measured using a VSM wherein the maximum applied magnetic field of 16kOe was applied

15 to the VSM sample. More specifically, the magnetization curves are respectively measured as to a parallel direction setting in that a direction of the magnetic field applied by the VSM is parallel to the magnetic field direction applied during the sample producing

20 process and as to a perpendicular direction setting in that a direction of the magnetic field applied by the VSM is perpendicular to the magnetic field direction applied during the sample producing process. Further, Js ratio (a ratio of the magnetization in the parallel direction

25 with respect to the magnetization in the perpendicular direction) at the magnetic field of 16kOe was evaluated. The magnitude of the Js ratio reflects that the hard magnetic phase region is large and the hard magnetic phase constructs a texture. Fig. 2 shows an example of

30 the measured result wherein the Js ratio was 1.7.

[0071]   Another VSM sample of the obtained thin strip alloy was produced by means of the same method employed

in the above production, and the magnetization curve in
the parallel direction with respect to the direction of
the magnetic field orientation of the produced sample was
measured as shown in Figs. 3 and 4. Fig. 4 is a

5   magnetization curve where the horizontal axis was
elongated ten times that of Fig. 3. As is recognized
from Figs. 3 and 4, the VSM sample of the obtained thin
strip alloy also exhibited the spring back phenomenon.
More specifically, when the decreased magnetic field was

10   inversely increased in the second and third quadrants of
the magnetization curve in the parallel direction, the
magnetization is increased as shown in Fig. 4.
Thereafter, when the measured magnetic field is decreased,
the increased curve was returned to a start point of the

15   inverse increase of the measured magnetic field. This
behavior was like as a spring characteristic, and thereby
called the spring back phenomenon (exchange spring
behavior). In the normal magnetization, the
magnetization does not increase by inversely increasing

20   the measured magnetic field in the way of decreasing the
measured magnetic field such in the second and third
quadrants of the magnetization curve in the parallel
direction. This spring back phenomenon exhibits that the
hard magnetic phase and the soft magnetic phase are

25   adjacently located, and that the interaction therebetween
is strong.

[0072]   A feature of the present invention is that a
rare earth magnet alloy is crystalline. In order to
check this feature, a differential thermal analysis (DTA)

30   was executed. As a result of this analysis, no clear
thermal peak was found.

[0073]   The obtained thin strip alloy was pulverized using a wet-type ball mill wherein the milling operation was executed using cyclohexane under argon atmosphere, and polybutenyl-succinimide-tetraethylenepentamine (1300

5 molecular weight) was used as dispersant. This dispersant included a small quantity of mineral oil. The obtained powder (rare earth magnet powder) was observed using the SEM. Fig. 5 shows a SEM photograph of the obtained powder whose powder sizes were smaller than or

10 equal to 1 μm and wherein there was found no powder larger than 1 μm in powder size.

[0074]   As to the as-milled powder, a VSM sample was produced in the same manner as discussed above, and the magnetization curves thereof were also measured. The

15 measurement result of the magnetization curves are shown in Fig. 6 wherein Js ratio thereof was 1.5. This means that the obtained powder also exhibited the anisotropy. As the coercive force thereof increased as compared with that in Fig. 2, it is estimated that the hard magnetic

20 phase thereof was a fine grained structure. Fig. 7 distinctively shows the spring back phenomenon represented in the magnetization curve along the parallel direction in Fig. 6.

[0075]   The magnet powder obtained by pulverizing the

25 base material was heat treated at 612°C. Then, as to the VSM sample of the obtained heat-treated magnet powder, the magnetization curves thereof were also measured. The measurement result of the magnetization curves are shown in Fig. 8 wherein the heat-treated magnet powder

30 exhibited the anisotropy and the Js ratio thereof was around 1.4 which is a reference value. Since the heat-treated powder was put in a flocculated state, the

magnetic field orientation in the VSM sample was insufficient and therefore the Js ratio was around 1.4. By further pulverizing the heat-treated powder by means of a set of mortar and pestle so as to release the

5   flocculated state in some degree, a VSM sample thereof was produced, and the magnetization curves thereof were measured. As a result, it was recognized that the Js ratio was largely improved. The coercive force of this sample was largely increased as compared with that shown

10   in Fig. 6 and was 6.4kOe. As a result of observing the structure of this powder, the hard magnetic phases and the soft magnetic phases were finely dispersed to form a mixed structure of the hard magnetic phases and the soft magnetic phases.

15   [0076]   Figs. 9A and 9B show X-ray diffraction results of the as-milled powder (a) and the powder (b) heat-treated at 612°C, respectively. As is apparent from Figs. 9A and 9B, the diffraction peaks of the powder (b) are sharpened. It is therefore assumed that the

20   as-milled powder (a) still remains relatively large quantity of stains therein, or includes amorphous phases.
[0077]   EXAMPLE 2

A thin strip of the rare earth magnet alloy was produced from an alloy ingot having a composition of

25   $Nd_{10}Fe_{75}Co_8B_6V_1$ by means of the strip casting method and in the same manner as EXAMPLE 1. It was observed that the thin strip alloy has had a mixed structure of the hard magnetic phases and the soft magnetic phases, as a result of observing a cross-section of the thin strip alloy by

30   means of SEM. Substantially the minimum width of the soft magnetic phases was smaller than or equal to 1 μm, and the minimum distance between the soft magnetic phases

was greater than or equal to 0.2 μm. Powder for a VSM
sample was produced by pulverizing the thin strip alloy
into a size smaller than 25 μm using a set of mortar and
pestle. The Js ratio of the VSM sample was 1.8.

[0078]   EXAMPLE 3

A thin strip of the rare earth magnet alloy was
produced from an alloy ingot having a composition of
$Nd_{11}Fe_{74}Co_8B_6V_1$ by means of the strip casting method and in
the same manner as EXAMPLE I. It was observed that the
thin strip alloy has had a mixed structure of the hard
magnetic phases and the soft magnetic phases, as a result
of observing a cross-section of the thin strip alloy by
means of SEM. Substantially the minimum width of the
soft magnetic phase was smaller than or equal to 1 μm,
and the minimum distance between the soft magnetic phases
was greater than or equal to 0.5 μm. Powder of a VSM
sample was produced by pulverizing the thin strip alloy
into a size smaller than 25 μm using a set of mortar and
pestle. The Js ratio of the VSM sample was 1.8.

[0079]   COMPARATIVE EXAMPLE 1

A thin strip of the rare earth magnet alloy was
produced from an alloy ingot having a composition of
$Nd_8Fe_{77}Co_8B_6V_1$ by means of the strip casting method and in
the same manner as EXAMPLE 1. It was observed that the
thin strip alloy has had a mixed structure of the hard
magnetic phases and the soft magnetic phases, as a result
of observing a cross-section of the thin strip alloy by
means of SEM. There were a lot of the soft magnetic
phases whose minimum widths were greater than 1 μm and
were substantially not smaller or equal to 1 μm. Further,
there was a tendency that the minimum distance between

the soft magnetic phases was smaller than 0.1 μm. Powder of a VSM sample was produced by pulverizing the thin strip alloy into a size smaller than 25 μm using a set of mortar and pestle. The Js ratio of the VSM sample was

5   1.2.

[0080]   EXAMPLE 4

A thin strip of the rare earth magnet alloy was produced from an alloy ingot having a composition of $Nd_{11}Fe_{72}Co_8B_{7.5}V_{1.5}$ by means of the strip casting method and

10   in the same manner as EXAMPLE 1. A condition of the strip casting method for producing EXAMPLE 4 was that a cooling speed for cooling the material to the solidification temperature of around 900°C was 2000°C/sec. It was observed that the thin strip alloy has had a mixed

15   structure of the hard magnetic phases and the soft magnetic phases, as a result of observing a cross-section of the thin strip alloy by means of SEM. Substantially the minimum width of the soft magnetic phase was smaller than or equal to 1 μm, and the minimum distance between

20   the soft magnetic phases was greater than or equal to 1 μm. Fig. 10 is a SEM photograph showing a center area of a cross section of the obtained thin strip alloy. Black stripes aligned along the direction from a left upper side toward a right lower side are the soft magnetic

25   phases of α-(Fe-Co). The other regions are the hard magnetic phase regions. That is, the hard magnetic phases are separated by the soft magnetic phases of stripes.

[0081]   As to the as-milled powder, a VSM sample was

30   produced in the same manner as EXAMPLE 1, and the magnetization curves thereof were also measured. The

measurement result of the magnetization curves were shown
in Fig. 11 wherein Js ratio thereof is a value slightly
greater than 1.5. It is assumed that even when the
powder is obtained by means of a ball mill, the same

5   result with EXAMPLE 1 is obtained. Fig. 12 shows the
magnetization curves of the powder heat-treated at 610°C.
The coercive force thereof was 9.0kOe and was greater
than that in Fig. 11. The reason for taking a small Js
ratio is the same as discussed above. That is, since the

10   heat-treated powder is put in flocculated state, the
magnetic field orientation in the VSM sample is not
sufficiently achieved. Fig. 13 shows a magnetization
curve of a sample produced in the same manner as that in
Fig. 12 in order to observe the spring back phenomenon.

15   As a result, this heat-treated magnet powder exhibited
the spring back phenomenon.
[0082]   In order to find a preferred condition of the
discharge plasma sintering, the following experiments
were carried out.

20   [0083]   REFERENCE EXAMPLE 1
         Rare earth magnet powder was obtained in the same
manner as EXAMPLE 1, that is, by pulverizing the thin
strip of the rare earth magnet alloy using a wet-type
ball mill. A compressed powder body was produced by

25   compressing the rare earth magnet powder at a pressure of
2 ton/cm^2 while treating the magnetic field orientation by
applying the magnetic field of 20kOe. A die employed in
this compressing process was a non-magnetic WC type. The
size of the compressed powder body was 10mm×10mm×7mm.

30   [0084]   A Nd-Fe-B type anisotropic exchange spring
magnet was obtained by forming a bulk from the compressed
powder body by means of the discharge plasma sintering

unit under a condition that the temperature is maintained at 650°C for 3 minutes while the compressing pressure of 9 ton/cm^2 is applied to the compressed powder body. The density of the exchange spring magnet reached the true

5   density.

[0085]   The obtained exchange spring magnet was observed using SEM and TEM. As a result of these observations, the obtained magnet had a mixed structure of hard magnetic phases and soft magnetic phases. The

10   crystalline grain size of the obtained magnet had a range from 15 to 40 nm. It was observed by TEM that the direction of the hard magnetic phases was aligned.

[0086]   REFERENCE EXAMPLE 2

A Nd-Fe-B type anisotropic exchange spring was

15   obtained in the same manner as REFERENCE EXAMPLE 1 except that the compressing pressure during the discharge plasma sintering was 8 ton/cm^2. The exchange spring magnet had a density which is 95% of the true density.

[0087]   REFERENCE EXAMPLE 3

20   A Nd-Fe-B type anisotropic exchange spring was obtained in the same manner as REFERENCE EXAMPLE 1 except that the compressing pressure during the discharge plasma sintering was 7 ton/cm^2. The obtained exchange spring magnet had a density which is 90% of the true density.

25   [0088]   REFERENCE EXAMPLE 4

A Nd-Fe-B type anisotropic exchange spring was obtained in the same manner as REFERENCE EXAMPLE 1 except that the temperature during the discharge plasma sintering was 810°C. The obtained exchange spring magnet

30   had the true density.

[0089]   The magnetization curves of REFERECE EXAMPLES 1 through 4 were measured using a direct-current BH curve

tracer which is capable of applying the maximum applied
magnetic field of 20kOe to the samples. TABLE 1 shows
the magnetization ratio (Js ratio 2) between the
magnetization in the direction of the magnetic field

5   orientation and the magnetization in the direction
perpendicular to the magnetic field orientation at the
magnetic field of 20kOe. The Js ratio 2 of REFERENCE
EXAMPLE 1 was 1.8 and was greater than Js ratio (1.7) of
EXAMPLE 1. Further, TABLE 1 shows energy product (BHmax)

10   obtained from each magnetization curve. As to the
coercive force, REFERENCE EXAMPLES 1 through 3 took
values around 7.0kOe, and REFERENCE EXAMPLE 4 took 5.0kOe.
TABLE 1 clearly represents that it is preferable that the
density of the magnet is greater than 95% of the true

15   density and that the sintering temperature in the
discharge plasma apparatus is lower than or equal to 800°C.

[0090]   TABLE 1

	COMPOSITION (atom%)	Js ratio 2	BHmax (MGOe)
REF. EXAMPLE 1	$Nd_{9.1}Fe_{75.8}Co_8B_{6.1}V_1$	1.8	25
REF. EXAMPLE 2	$Nd_{9.1}Fe_{75.8}Co_8B_{6.1}V_1$	1.8	20
REF. EXAMPLE 3	$Nd_{9.1}Fe_{75.8}Co_8B_{6.1}V_1$	1.8	18
REF. EXAMPLE 4	$Nd_{9.1}Fe_{75.8}Co_8B_{6.1}V_1$	1.5	15

[0091]   EXAMPLE 5

20   The exchange spring magnet of REFERENCE EXAMPLE 1
was applied to a surface permanent magnet motor having a
12-pole stator and 8-pole rotor. Fig. 14 is a cross
section of 1/4 part of the surface permanent magnet motor
of a concentrated winding type to which the exchange

25   spring magnet is applied. An outer side of the motor in
Fig. 14 is an aluminum case 11, and an inner side thereof

is the stator 12 having 52mm inner diameter and 108mm outer diameter. 1-2 is u-phase coil, 3-4 is v-phase coil, and 5-6 is w-phase coil. Stator 12 is a laminated member of electrical steel sheets. A plurality of magnets 13

5   are installed in a rotor core 14. The maximum outer diameter of the rotor is 50.7mm, and the total thickness of the stator and the rotor was 79.8mm.

[0092]   The performance of the motor was that the maximum rated output was 2kW, the temperature limitation

10   was 160°C. The coercive force of the exchange spring magnet was 7.2kOe. On the other hand, if a conventional Nd-Fe-B sintered magnet is employed in a motor, the magnet is required to have the coercive force more than 19.8kOe in order to ensure the temperature limit as same

15   as that using the magnet of REFERENCE EXAMPLE 1. That is, the motor employing the magnet according to the present invention gave a superior performance in thermal design.

[0093]   This application is based on prior Japanese Patent Application No. 2002-328579. The entire contents

20   of the Japanese Patent Application No. 2002-328579 with a filing date of November 12, 2002 are hereby incorporated by reference.

[0094]   Although the invention has been described above by reference to certain embodiments of the invention, the

25   invention is not limited to the embodiments described above. Modifications and variations of the embodiments described above will occur to those skilled in the art in light of the above teachings. The scope of the invention is defined with reference to the following claims.